PATENT SPECIFICATION

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DRAWINGS ATTACHED.

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COMPLETE SPECIFICATION.

Improvements relating to an Electron Cyclotron Resonance Ultra-Violet Lamp.

We, KABUSHIKI KAISHA HITACHI SEISAKUSHO, a joint-stock company of Japan, of 12, 2-Chome, Marunouchi, Chiyoda-Ku, Tokyo-To, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:

This invention relates to an electron cyclotron resonance lamp for generating far ultraviolet radiation. Such a device is of great importance and value for such work as spectroscopic analysis and research on photo-chemical reactions.

As is known, the range of light wave lengths from several angstroms to 2000 angstroms is generally referred to as the "far ultraviolet region". This region is also known as the "vacuum ultraviolet region", since, in such work as experimental spectroscopic analysis in this wave-length region, vacuum spectrometers are required because of absorption due to air. Because the spectra of molecules, atoms, and ions having excitation energies of approximately 6 eV or more fall within this region, far ultraviolet spectroscopy is indispensable in the study of the molecular structures and the electronic states of such molecules, atoms, and ions. Furthermore, for ultraviolet spectroscopic technique is considered to be necessary for measurement of high-temperature plasmas since high-temperature plasmas of several tens of thousands of degrees Kelvin emit far ultraviolet light. This technique is also applied to such observations as those of the sun, stars, and night sky and is useful for attaining knowledge relating to space.

When this technique is further applied to spectroscopic analysis the technique is of great importance in the analysis of non-metallic impurities in the refining processes of steel and other metals, because the intense spectrum lines of non-metallic elements are within the far ultraviolet region. For example, the sensitive lines of substances such as carbon, phosphorus, and sulphur of relatively high compositional content in iron and steels are within the far ultraviolet region; accordingly, quality control of even higher precision than that possible heretofore should become possible with progress in techniques in far ultraviolet spectroscopic analysis.

In this far ultraviolet region, however, difficulties such as lowering of transparency reflection coefficients of prisms and reflecting mirrors and the lowering of the detector sensitivity are encountered. For this region, a light source of an intensity as high as available is required. Among the light sources used heretofore, many have been of the type in which capacitors charged to high voltages of approximately 10,000 volts are discharged in a vacuum; examples of such sources are hot spark devices, sliding spark devices, and the Lyman tube. However, in all of these devices, reproducibility is poor, and the serviceable life is short because of erosion of such parts as electrodes and tube wall. Furthermore, since high voltage is used, these devices have further disadvantages such as the occurrence of discharge between the discharge tube and the spectrometer or the contamination of the spectrometer interior by the spatter of the electrodes and tube wall.

In addition, light sources in which a continuous discharge in hydrogen gas or rare gases instead of capacitor discharge is utilized are also known. In the case of many of these light sources, however, the greater part of the radiation is in the visible or ultra-

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violet region, and the far ultraviolet radiation is weak. The reason for this is that the temperature of the plasma within the discharge tube is low, and intense far ultraviolet rays are not radiated from a plasma of a temperature below 10,000 degrees Kelvin generated by ordinary discharge. The basic reason for this deficiency will now be considered in some detail.

The distribution of atoms or ions in the states of exciting energy under the condition of thermal equilibrium may be expressed by the so-called Boltzmann factor $\exp(-E/kT)$, where E is the excitation energy, k is the Boltzmann constant, and T is temperature (degrees K). When the said factor is calculated for excitation energy (approximately 6 eV) corresponding to a wavelength of 2000 angstroms, the result is approximately 1/1000 for $T = 10{,}000$ deg. K, approximately 1/30 for $T = 20{,}000$ deg. K, and approximately 1/10 for $T = 30{,}000$ deg. K. That is, by increasing the temperature three times, the intensity of light of 2000-angstrom wavelength is increased 100 times. This ratio of intensity increase becomes even greater with shorter wavelengths. Accordingly in order to cause the radiation of considerably intense far ultraviolet rays from light sources used at present, it is desirable that the temperature be at least 20,000 degrees K and preferably 30,000 degrees K or higher.

An important point to be noted here is that, for radiation of far ultraviolet rays, it is not necessary for all of the particles in the plasma to be equally at a temperature of 20,000 to 30,000 degrees K or higher. The reason for this is that excitation and ionization of gas atoms are accomplished principally by the collision of high-velocity electrons with these gas atoms, and, provided that the kinetic energy of the electrons can be increased, the aim of generating far ultraviolet rays is attained. More explicitly, causing the mean kinetic energy possessed by the electrons to increase, that is, in equivalent effect, elevating the electron temperature and preventing unnecessary kinetic energy from being supplied to ions and other gas particles are the fundamental conditions for generating far ultraviolet radiation with high efficiency.

In view of the foregoing considerations, it is an object of the present invention to provide an electron cyclotron resonance ultra-violet lamp for generating a special, high-temperature plasma which, with relatively low power supply, accomplishes generation of the above-mentioned far ultraviolet radiation. According to the present invention, there is provided an electron cyclotron resonance ultra-violet lamp comprising means for creating a plasma existing in a magnetic field and means for supplying electromagnetic radiation energy at a frequency such as to cause resonance absorption of the said electromagnetic radiation due to the electron motion within the said plasma, whereby the electron temperature, which is equivalent to the mean kinetic energy, of the electrons within the said plasma is caused to be at least 20,000 degrees Kelvin, and the said plasma is caused to be in a state of high energy excitation such that the said plasma is capable of producing radiation of a wavelength of 2,000 angstroms or less.

In order to facilitate a clear and full understanding of the principle and nature of the invention, the following analytical description is presented.

A plasma of electron density N (cm^{-3}) existing in a magnetic field of magnetic flux density B (kilogauss) will be considered. The properties of this plasma can be expressed by two representative quantities. The first quantity represents the collective motion of the electrons and is commonly called the plasma oscillation frequency. When denoted by f_p, this quantity is expressed by the following equation.

$$f_p = 8900 \times \sqrt{N} \text{ (c/sec.)} \quad \ldots\ldots\ldots \quad (1)$$

The second important quantity is the gyration frequency produced when the individual electrons become encompassed about the magnetic flux and undergo so-called cyclotron gyration. When denoted by fc, this quantity is expressed by the following equation.

$$f_c = 2800 \times B \text{ (Mc/sec.)} \quad \ldots\ldots\ldots \quad (2)$$

If an electromagnetic wave of frequency f is projected into the plasma described above, the electromagnetic wave will be intensely absorbed by the plasma at a certain frequency and only at this frequency. As is well known, this phenomenon, which has been determined theoretically and confirmed experimentally, is caused by the resonance the afore-mentioned three frequencies, namely, the characteristic frequencies fp and fc of the electrons within the plasma and the frequency f of the incident electromagnetic wave, and is commonly referred to as electron cyclotron resonance absorption. The condition for the occurrence of this resonance when the direction of propagation of the electromagnetic wave is parallel to the magnetic field is that the frequency f be approximately as follows:

$$f = f_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The said condition when the direction of the propagation of the electro-magnetic wave and magnetic field are mutually perpendicu-

lar is that the frequency f be approximately as follows:

$$f = \sqrt{f_p^2 + f_c^2} \quad (4)$$

Since this resonance absorption is due to individual or collective motion of the electrons, and the ions or atoms do not participate directly in this resonance absorption, the process of energy transfer from the electromagnetic wave to the electrons is accomplished with extremely high efficiency.

A preferred embodiment of the invention is illustrated in the accompanying drawing which is a schematic sectional diagram.

Referring to the drawing, the plasma of the device is created within a discharge tube 1 made of an insulator such as glass, containing a sealed-in gas at a low pressure of the order of 1μ Hg. This gas can be any gas. Electrodes 2 and 3 are disposed at opposite ends of, and within, the discharge tube 1 and have the function of maintaining a direct-current or low-frequency subsidiary discharge. Coils 6 and 7 surround the exterior periphery of the discharge tube 1 and function to create an axial magnetic field, which causes a plasma 4 generated by the aforesaid subsidiary discharge to have a tendency to be confined substantially on the central axis as indicated by the dotted lines in the drawing.

An incident electromagnetic wave is supplied from a high-frequency power source 8 to a square wave guide 9. Since the discharge tube 1 is disposed through the side walls of the wave guide 9, the electromagnetic wave propagating through the wave guide 9 is projected into the plasma 4 in a direction perpendicular to the magnetic field. Accordingly, the oscillation frequency at which the electromagnetic wave gives rise to resonance absorption within the plasma 4 is determined from the aforesaid Equation (4).

As an example, when the magnetic flux density B is 3 kilogausses, the cyclotron oscillation frequency is given from Equation (2) as $f_c \simeq 8700$ (Mc/sec.). Moreover, when the electron density within the plasma is 10^{11} (cm^{-3}), the plasma oscillation frequency is given by Equation (1) as $f_c \simeq 2800$ (Mc/sec.). Accordingly, the resonance frequency is given by Equation (4) as

$$f = \sqrt{f_p^2 + f_c^2} \simeq 9100 \text{ (Mc/sec.)}.$$

That is, when a micro-wave of a frequency of 9100 (Mc/sec.) is directed into the plasma 4, an intense, mutual interference is caused, and the micro-wave power is absorbed by the electrons within the plasma. During this operation, it is possible that some power passes through without being absorbed by the plasma. However, since this power is reflected by one end 10 of the wave guide 9 and is directed again into the plasma, the quantity of ineffective power is extremely small.

It is preferred to use a magnetron for the high-frequency power source 8, and its operation may be either continuous operation or repeated-pulse operation.

In the device of this invention of the above-described construction, the electrons within the plasma absorb micro-wave power, and it is possible to maintain, constantly, electron temperatures of 20,000 to 30,000 degrees K or higher. From the plasma of such extremely high temperature, light rays in the far ultraviolet region are emitted as a parallel-ray light beam through a passage opening 5 provided in the centre of the electrode 3.

It is to be observed from the foregoing description that the electron cyclotron resonance ultra-violet lamp according to the present invention, differing from a simple plasma generating device of direct-current or low-frequency discharge type, is one in which a high-frequency electromagnetic wave is supplied into a plasma to cause the power of the electromagnetic wave to be absorbed by the electrons within the plasma, that is, to cause so-called electron cyclotron resonance absorption to take place, and energy is supplied to only the electrons within the plasma, whereby a plasma of extremely high temperature, which has heretofore been unattainable, is generated with extremely high efficiency. Accordingly, the present invention provides a light source for far ultraviolet radiation requiring relatively lower power and is particularly applicable to spectroscopic analysis, photochemical reaction, and research on such subjects as the energy levels of atoms.

WHAT WE CLAIM IS:—

1. An electron cyclotron resonance ultraviolet lamp comprising means for creating a plasma existing in a magnetic field and means for supplying electromagnetic radiation energy at a frequency such as to cause resonance absorption of the said electromagnetic radiation due to the electron motion within the said plasma, whereby the electron temperature, which is equivalent to the mean kinetic energy, of the electrons within the said plasma is caused to be at least 20,000 degrees Kelvin, and the said plasma is caused to be in a state of high energy excitation such that the said plasma

is capable of producing radiation of a wavelength of 2,000 angstroms or less.

2. An electron cyclotron resonance ultraviolet lamp substantially as described with reference to the accompanying drawing.

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1 SHEET This drawing is a reproduction of the Original on a reduced scale